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A GaAs-Based MOEMS Tunable RCE Photodetector with Single Cantilever Beam*

Zhou Zhen[1], Han Qin[2], Du Yun[2], Yang Xiaohong[2], Wu Ronghan[2], Huang Yongqing[1], and Ren Xiaomin[1]

(1 Optical Communication Center, School of Telecommunication Engineering, Beijing University of Posts and Telecommunications, Beijing 100876, China)

(2 State Key Joint Laboratory of Integrated Optoelectroics, Institute of Semiconductors, Chinese Academy of Sciences, Beijing 100083, China)

Abstract: A GaAs-based micro-opto-electro-mechanical-systems (MOEMS) tunable resonant cavity enhanced (RCE) photodetector with a continuous tuning range of 31nm under a 6V tuning voltage is demonstrated. The single cantilever beam structure is adopted for this MOEMS tunable RCE photodetector. The maximum and minimum peak quantum efficiency during the tuning are 36.9% and 30.8%, respectively. The maximum and minimum full-width-at-half-maximum (FWHM) are 20nm and 14nm, respectively. The dark current density is 7.46A/m^2 without bias.

Key words: GaAs; MOEMS; RCE; photodetector; tuning; single cantilever beam

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1 Introduction

Optical fiber and wavelength division multiplexed (WDM) communication systems have led to great increase in available transmission bandwidth and routing and interconnect schemes. Despite these great advantages, the practical implementation of the WDM network has been limited by the availability of suitable and inexpensive multiwavelength sources and detectors[1]. Micro-opto-electro-mechanical-systems (MOEMS) tunable optoelectronic devices such as wavelength tunable filters[2,3], vertical cavity surface emitting lasers (VCSELs)[4,5], light emitting diode (LED)[6], and detectors[1] fabricated by MOEMS technology are attractive for WDM purposes due to their wide continuous tuning range and potential low cost. These MOEMS optoelectronic devices realize the tunability using distributed Bragg reflectors (DBR) and cantilever beams.

In this paper, we present a GaAs-based MOEMS tunable RCE photodetector with single cantilever beam fabricated by a developed technology which is compatible with the technologies of standard surface micromaching and photodetector fabrication. Fabrication and demonstration of this MOEMS tunable RCE photodetector has been reported. The device achieves 31nm continuous tuning range under a low 6V tuning voltage and the characteristics over tuning range are basically uniform. The MOEMS tunable RCE photodetector, which is part of a family of surface normal devices, is ideal for robust WDM systems and lowers the component cost by reducing the wavelength selection, aging, and environment tolerances placed on the

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Zhou Zhen male, PhD candidate, was born in 1976. His current interest is in semiconductor optoelectronic devices. Email: zhou405@263.net

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sources.

2 Principles of MOEMS tunable RCE photodetector

The RCE photodetector is a part of a family of RCE type devices[7]. The performances of these RCE type devices are improved by placing the active layers structure inside a Fabry-Perot resonant cavity. Such RCE type devices benefit from the wavelength selectivity and the large increase of the resonant optical field introduced by the resonant cavity. For the RCE photodetector, the increased optical field allows the RCE photodetector active layers structure to be thinner and thus faster, while simultaneously increasing the quantum efficiency at the resonant wavelength. Since off-resonance wavelengths are rejected by the cavity, RCE photodetectors having both wavelength selectivity and high speed response make them ideal for WDM applications. Commonly the RCE photodetector consists of top and bottom DBRs, an active region sandwiched between two spacer layers, and a semi-insulating substrate. The quantum efficiency can be determined following a procedure similar to the one in Ref. [7]. Applying this method, the quantum efficiency η as a function of wavelength λ can be expressed as

$$\eta = \frac{1 + R_2 e^{-\alpha d}}{1 - 2\sqrt{R_1 R_2} e^{-\alpha d} \cos(2\beta L + \psi_1 + \psi_2) + R_1 R_2 e^{-2\alpha d}} \times (1 - R_1)(1 - e^{-\alpha d}) \quad (1)$$

where R_1 and R_2 are the reflectivities of the top and bottom DBRs, respectively, α and d are the absorption coefficient and thickness of the active layers, respectively, L is the length of the resonant cavity, and β is the propagation constant. Assuming αd is a certain value, the maximum quantum efficiency occurs at

$$R_1 = R_2 e^{-2\alpha d} \quad (2)$$

The details about the RCE structure design can be found in Ref. [7].

For the MOEMS tunable RCE photodetector, the tunable part is based on a Fabry-Perot (F-P) interferometer, consisting of two parallel mirrors with high reflectivity. The absorbing wavelength of the RCE photodetector can be modulated by shifting the F-P resonance, either by modulating the refractive index or the effective length of the cavity. Large wavelength tuning range can be realized by modulating the effective cavity length. Almost all MOEMS tunable devices typically have an air-gap cavity sandwiched by dielectric or semiconductor DBRs. The movable DBR is held by cantilever beams. Wavelength tuning is accomplished by applying a voltage between the top and bottom DBRs across the air-gap cavity. A reverse bias voltage is used to provide the electrostatic force, which attracts the cantilever beam downward to the substrate and shorten the air-gap cavity, thus tuning the mode wavelength toward a shorter wavelength. The wavelength shift, $\Delta\lambda$, changes linearly with the cavity length change,

$$\frac{\Delta\lambda}{\lambda_0} = \gamma \frac{\Delta L}{L_0} \quad (3)$$

where ΔL is the cavity length change, and γ is a constant dependent on the optical structure of the F-P cavity, λ_0 and L_0 are the initial center wavelength and resonant cavity length, respectively. Because wavelength tuning is realized by mechanically modulating the effective length, this wavelength tuning technique does not suffer from the shortcomings of the thermal tuning technique for which the tuning speed is slow and the tuning range obtainable is limited[8,9].

The bandwidth of its transmittance spectrum is characterized by FWHM[2],

$$\mathrm{FWHM} = \frac{\lambda_0^2 (1 - \sqrt{R_1 R_2})}{2\pi n L_0 (R_1 R_2)^{1/4}} \quad (4)$$

where n is the refractive index of the cavity.

The air-gap cavity is modulated by applying an electrostatic bias between the top and bottom electrodes. The maximum deflection is determined by the mechanical property of the cantilever beams as well as the capacitive nature of the attractive force.

A simple analytic approximation is given here[4] ,

$$z = \frac{\pi r^2 \varepsilon}{E} \times \frac{2l^3}{wt^3} \times \frac{U^2}{(d - z)^2} \qquad (5)$$

where z is the vertical displacement of the cantilever beam, ε is the dielectric constant of the air, d is the air-gap cavity thickness without applied voltage, U is the applied voltage, E is the Young's modulus of the cantilever, r, l, w, and t are radius, length, width, and thickness of the cantilever beam, respectively.

It can be derived from Eq. (5) that a parabolic relationship is between the movable DBR vertical displacement and the applied voltage because the movable DBR and the substrate form a parallel plate capacitor. It can be seen that reducing the thickness, the width of the cantilever beam and the original thickness of the air-gap cavity, or increasing the length of the cantilever beam, or reducing the numbers of the cantilever beam can result in the decrease of the applied voltage.

3　Design and fabrication

The epitaxial structure of the vertical-cavity device is commonly designed using the transfer-matrix method[7]. During the design process for the MOEMS tunable RCE photodetector, the decisions of materials, positions and thicknesses of DBRs, sacrificed layers, quantum well absorbing layers, ohmic contact layers, and so on are very important to ensure the optimal performance of the device. Furthermore, the optimization of the fabrication process should also be taken into account in order to make the fabrication as easy as possible.

Figure 1 is a schematic diagram of epitaxial structure of the device grown on the n-doped GaAs substrate by metal organic chemical vapor deposition (MOCVD). A resonant cavity photodetector was formed by incorporating 6. 5 pairs $In_{0.2}Ga_{0.8}As$/GaAs strained quantum wells absorbing layers between two DBRs. The top and bottom DBRs were composed of 8. 5 and 23 pairs n-type GaAs/$Al_{0.8}Ga_{0.2}As$ 1/4 wavelength stacks, respectively. The sacrificed layer was AlAs. The p doped GaAs spacer layer below the sacrificed region should be heavily doped in order to obtain good ohmic contact. The resonant mode of epitaxial structure was designed at 980nm.

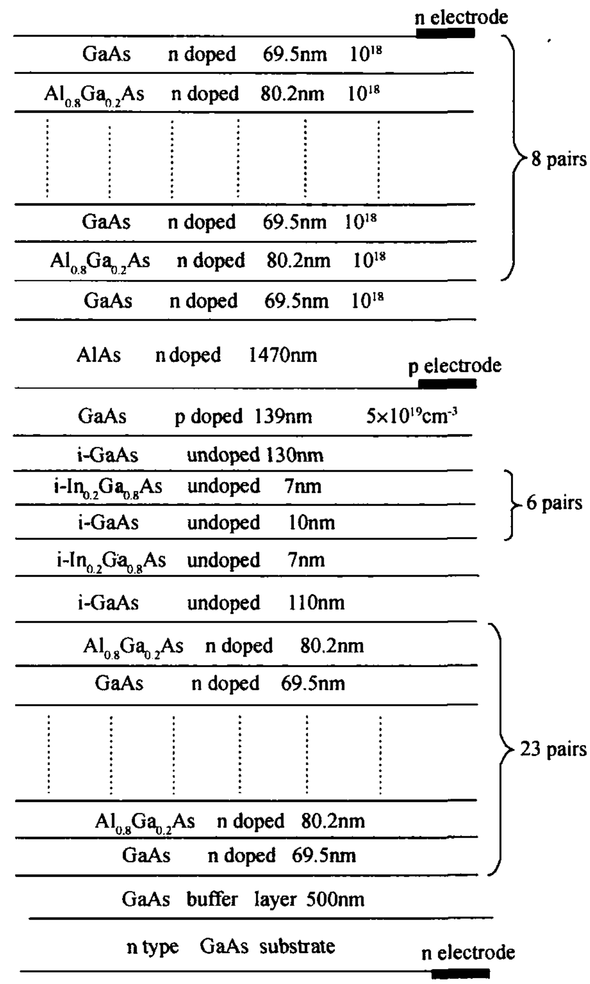

Fig. 1　Schematic diagram of epitaxial structure of the MOEMS tunable RCE photodetector

As the maximum deflection of the cantilever beams approximates 1/3 air-gap cavity (referred to as the 1/3-rule, can be obtained by solving Eq. (5)), it is natural to assume the larger air-gap cavity is better. However, increasing the air-gap cavity leads to a longer effective cavity length, which results in a narrower F-P mode separation, and thus a smaller overall tuning range. Moreover, increasing the air-gap requires higher tuning voltage. Hence, an optimum design is needed. We select the thickness of the air-gap cavity to be 1. 5λ.

The MOEMS tunable RCE photodetector schematic structure was shown in Fig. 2. In order to reduce the tuning voltage, we adopted the single cantilever beam structure. The movable top DBR was supported in a freely suspended cantilever beam. The formation of the air-gap cavity was accomplished by selective etching of the AlAs sacrificed layer against $GaAs/Al_{0.8}Ga_{0.2}As$ materials. The two mesas in the device structure were formed by non-selective etching process to expose the sacrifice layer and isolate the devices, respectively. There are three electrodes on the surfaces of the top DBR, the high-doped GaAs layer, and the bottom of the substrate, respectively. The n and p type electrodes on the surfaces of the top DBR and the high-doped GaAs layer created the electrostatic attraction changing the thickness of the air-gap cavity. The n type electrode on the bottom of the substrate and the p type electrode on the surface of high-doped GaAs layer created the bias voltage of the photodetector.

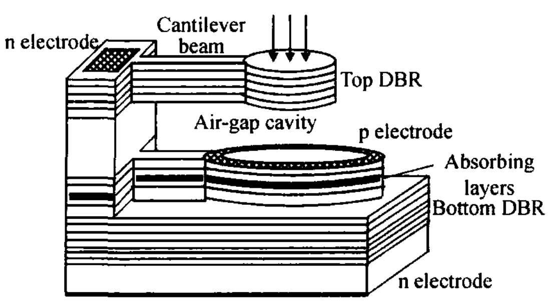

Fig. 2 Schematic structure of the MOEMS tunable RCE photodetector

The length and width of the cantilever beam were 170 and 20μm, respectively. The center DBR was a circle with a 60μm diameter. According to Eq. (2), for the top normal-incident RCE photodetector, the reflectivity of the top DBR has a optimum value, so the thickness of the cantilever is fixed (the reflectivity of the DBR is determined by the pairs of the 1/4 wavelength stacks.). The thickness of the top movable DBR of the device which was optimized according to Eq. (2) was only 1.27μm.

We utilized a developed technology which is compatible with the technologies of standard surface micromaching and photodetector fabrication. The most important process steps in fabricating are the formation of high quality air-gap cavity, the decreasing of dark current, and the elimination of the sticking and collapsing phenomena. More details about the non-selective and selective etching technologies to form the air-gap cavity in the developed fabrication process can be found in Ref. [10]. Figure 3 shows the SEM photo of the air-gap cavity of the device formed successfully by these etching technologies. The dark current is due to the shortcomings of a serial of process steps such as crystal growth, substrate cleaning, SiO_2 deposition and peeling, and so on. The sticking and collapsing phenomena which are very ordinary in the MOEMS fabrication process have been eliminated basically by using some new process, while there is still much more effort devoted to decreasing the dark current of the device by optimizing the fabrication processes. The optical microscopy image of the fabricated MOEMS tunable RCE photodetector is shown in Fig. 4.

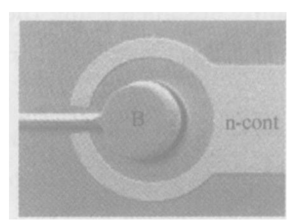

Fig. 3 SEM photo of the air-gap cavity of MOEMS tunable RCE photodetector

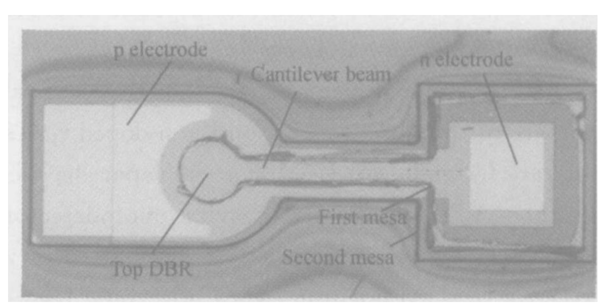

Fig. 4 Optical microscope image of the MOEMS tunable RCE photodetector

4 Results and discussion

Using a micro-spot spectrum analyzing system, the MOEMS tunable RCE photodetector response spectrum was measured. The incident monochromatic light of varying wavelengths produced by decomposing a beam of white light by grating was focused on the top DBR of the device whose photodetector was biased by 3V DC. The photoelectric response of the device was low without bias. The measured representative response spectra were shown in Fig. 5. As increasing the tuning voltage from 0 to 6V, the F-P wavelength shifted 31nm from 965nm to 934nm. During the course of tuning, the peak quantum efficiencies of the device under 3V bias reached the maximum 36.9% and minimum 30.8% responsing at the 950nm and 965nm, respectively, and the change range of the peak quantum efficiency was below 7%. The maximum peak quantum efficiency was far lower than the theoretical value (95%), which was due to the lack of an anti-reflection coating at the top surface and the light scatter loss at the interfaces of the air-gap cavity and semiconductor materials. The wavelength shift versus the applied voltage for the device is shown in Fig. 6. It is obvious that they have a good parabolic relationship which agrees with Eq. (5) well.

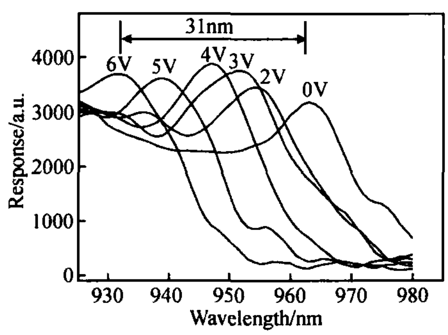

Fig. 5　Measured response spectra of the device under different tuning voltage　The photodetector is biased by 3V DC.

The maximum and minimum FWHM of the device during tuning were 14nm and 20nm responsing at the 950 and 934nm respectively. The FWHM broadening phenomenon during tuning is obvious. The broadening of the FWHM was mainly caused by the cavity length undulation which is originated from the deviation of the DBR thickness[11]. The deformation of the DBR during tuning and drawbacks in epitaxial materials of the DBR could broaden the FWHM of the device too. Besides these factors, the wider incidence and emission slots of monochromator also resulted in the FWHM broadening. It's available to decrease the FWHM of the device by improving the crystal quality or utilizing a tunable laser as the source.

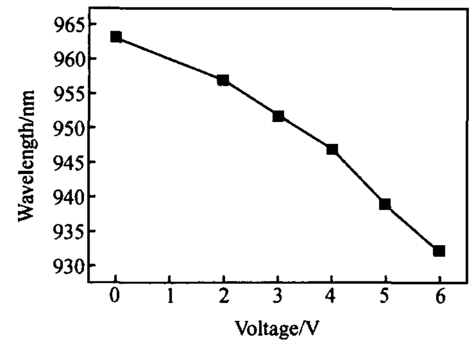

Fig. 6　Wavelength shift versus applied voltage for the device

The dark current results of the device under different bias are shown in Fig. 7. The dark current is 4.59×10^{-7} A at 0V, which corresponds to a dark current density of $7.46 A/m^2$, which was exceedingly high for a photodetector, and the dark current density increases rapidly with the bias increasing. The high dark current (which also means low signal

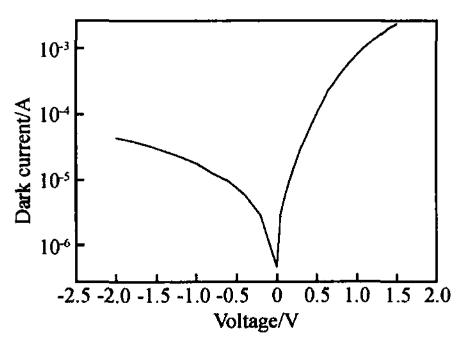

Fig. 7　Dark current of the device under different bias

to noise ratio) is due to the excessive drawbacks and dislocations in depletion layers of the quantum wells and unperfect fabrication process techniques.

In the course of fabrication and testing, we found the mechanical reliability and strength of the cantilever beams were weak which resulted in the failure of many devices. Especially during the selective wet etching process, the cantilever beams of many devices often collapsed because of capillary forces[12,13]. Although we adopted some effective ways to eliminate the capillary forces, the mechanical strength of the device are still to be increased in future work by using a four-arm cantilever structure[14], or increasing the thickness of the cantilever beams[15] without deteriorating the optical characters, and so on.

5 Conclusion

In summary, we have demonstrated a GaAs-based MOEMS tunable RCE photodetector with a single cantilever beam. The device has a 31nm tuning range under a low 6V applied voltage. During the tuning, the maximum value and the change range of peak quantum efficiency are 36.9% and below 7%, respectively. The minimum and maximum FWHM are 14nm and 20nm, respectively. The dark current density is 7.46A/m^2. It is the first time in China to fabricate this MOEMS tunable photodetecotor successfully.

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单悬臂梁结构的 GaAs 基 MOEMS 可调谐 RCE 光探测器 *

周　震[1]　韩　勤[2]　杜　云[2]　杨晓红[2]　吴荣汉[2]　黄永清[1]　任晓敏[1]

(1 北京邮电大学电信工程学院 光通信中心, 北京　100876)

(2 中国科学院半导体研究所 集成光电子学联合国家重点实验室, 北京　100083)

摘要: 成功研制了 GaAs 基 MOEMS 可调谐 RCE 光探测器. 该器件采用单悬臂梁结构,在 6V 的小调谐电压下,获得了 31nm 的连续调谐范围. 在调谐过程中,峰值量子效率最大为 36.9%,最小为 30.8%; FWHM 最大为 20nm,最小为 14nm. 在 0V 偏压下器件的暗电流密度为 7.46A/m^2.

关键词: GaAs; MOEMS; RCE; 光探测器; 调谐; 单悬臂梁

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周　震　男,1976 年出生,博士研究生,研究方向为半导体光电子器件. Email:zhou405@263.net

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